In-flight Wavelength Assignment:

Correcting for inhomogeneous slit illumination

Summary:
Due to inhomogeneous illumination of the entrance slit of OMI in the flight direction, wavelength shifts of up to 0.5 pixels occur within a single integration period. This document describes how and how well the algorithm that currently runs in the GDPS corrects for this.
The main conclusion is that the correction works well and that it is possible that the specification on the accuracy of the wavelength scale in the L1B product of 0.01 pixel (UV-2 and VIS) and 0.02 pixel (UV-1) can be reached.

		Date	Signature
Author:	Robert Voors	March 17^{th}, 2005	
Checked:			
Approved:			
Archive:			

Distribution list:

OMI Science team

Ruud Dirksen	KNMI
Marcel Dobber	KNMI
Pieternel Levelt	KNMI
Bert van den Oord	KNMI
Pepijn Veefkind	KNMI
Robert Voors	KNMI

Industry

Johan de Vries	Dutch Space

Change status:

Issue	Date	Comments	Affected pages
1	March 17th, 2005	First issue	All

1 Purpose

The purpose of this document is to show how and how well the correction algorithm for the inhomogeneous slit illumination works. A brief overview of the results leading up to change in the GDPS is given. Then the workings of the correction algorithm are explained. Subsequently an overview of how well the correction works is given. At the end some suggestions for further work in this area are given.

2 Table of contents

3 Referenced documents

- TN-OMIE-KNMI-613, “WP6: Temperature dependence of the wavelength calibration of OMI”, July 2004
- TN-OMIE-KNMI-691, “Wavelength Calibration Issues: Stability along the orbit worse than expected”, September 2004

4 Introduction

As indicated in the document "Wavelength Calibration Issues: Stability along the orbit worse than expected" (TN-691), the wavelength scale of the OMI spectra changes rapidly along the orbit. This effect is tentatively caused by non-homogeneous illumination of the OMI entrance slit in the flight direction (e.g. clouds). It was also shown that these variations correlate nicely with the change in signal between two integration periods. As a result, a method was conceived to use the small pixel radiances at one wavelength in the UV2 and VIS channels to account for these rapid changes in wavelength scale in the wavelength assignment step in the 0-1 data processor. This method is explained in (TN-691). Consequently it was decided to make a change in the way the GDPS assigns wavelengths to pixels. Also, in order for this algorithm to work, a new set of OPF parameters was calculated. After giving a brief overview of how the correction method works, it is shown in this document that that the algorithm as implemented in the GDPS works as expected.

5 How to correct for the wavelength shifts?

5.1 Where in the processing stream?

In TN-691 two different solutions to the problem were proposed:

1. Correction during the wavelength assignment step.
2. Correction as a post-processing step.

For a while an ad-hoc post-processor was tried out, but it turned out that the first option is the best. It was decided to update the wavelength assignment algorithm in the GDPS.

5.2 Can we use calibrated data?

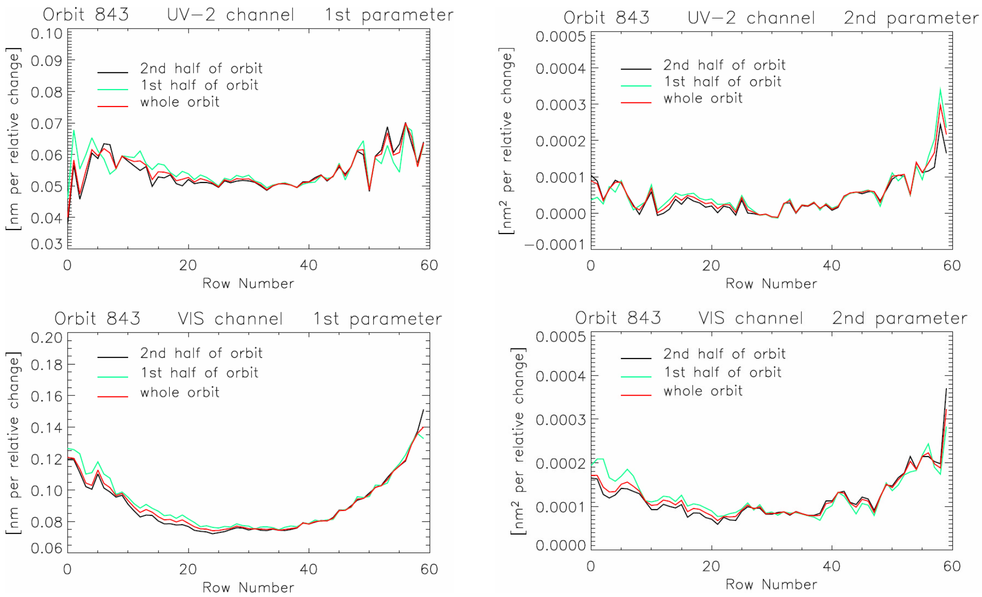
A minor difficulty in this approach lies in the determination of the correction parameters that scale the <*change in small pixel radiance*> to a <*change in wavelength parameters*>. The difficulty lies in the fact that in order to derive these dependencies it was only possible to use the flux-calibrated output of the L1B processor. (In principle, the debug option of the L1B processor can provide the necessary intermediate results, but this turned out to be practically unworkable, since output files were getting too large.) However, the problem turns out not to be serious. The reason for this is that the correction made is based on the **relative** change of the small pixel radiances. At the point in the L1B processing where the wavelength assignment is done, the radiometric conversion still has to take place. However, all the additive signal corrections have been made (e.g. stray light, dark current and offset correction). So, in effect it makes no difference whether the correction parameters are derived before or after the radiometric conversion, since scaling the signal will not change its relative variations.

5.3 Deriving correction parameters

The way to derive correction parameters is:

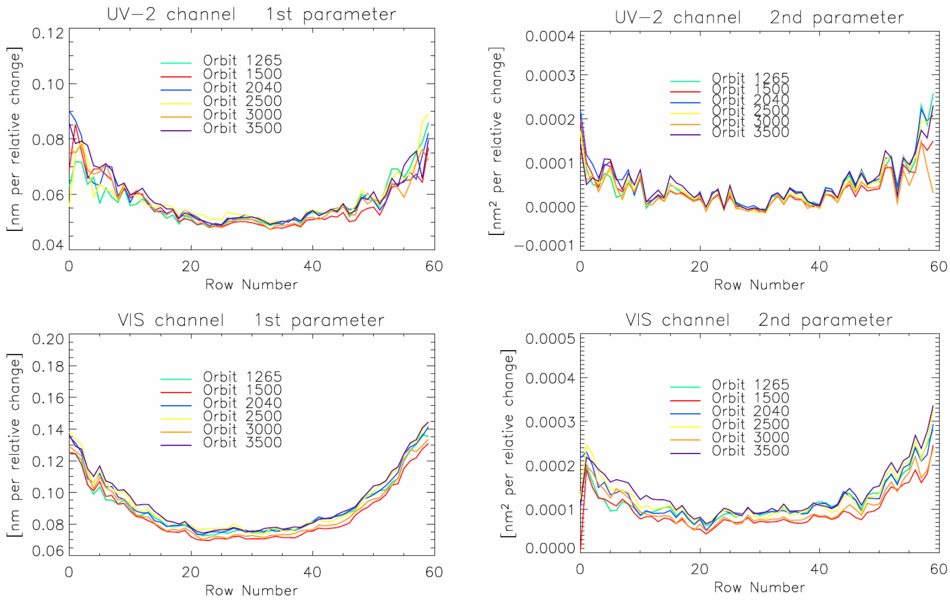
- Modify the OPF such that wavelength calibration is performed for all swath angles and process one entire orbit.
- Determine for the same orbit (all images, all swath rows) the relative change in the small pixel radiance per master clock period.
- Divide the former by the latter to obtain the correction parameters.

A number of issues remain to be addressed. First: are the derived parameters valid for the entire orbit and are they stable between different orbits? It turns out that the answer is yes in both cases. If values derived for the first half of the orbit are compared with with those for the second half, the differences are sufficiently small. As an indication two examples are shown for a single orbit, for the first and the second parameters.



Derived raw OPF parameters for separate sections of the orbit.

Also, comparing results of two separate orbits shows that the derived parameters are stable in time. So, in order to improve the statistics and hence lower the noise, the results of a number of different orbits were averaged when deriving the parameters for the OPF.



Derived raw OPF parameters for different orbits.

5.4 Structure in the row direction.

As can be seen in the above figures, there is quite some structure of the derived parameters in the row direction. From comparing the different orbits and the different sections of the orbit, we know this is not due to poor statistics. The origin of these row structures is currently unknown. The broad shape in the first parameter could possibly be understood in terms of decreasing spatial resolution. The more rapid changes in the row direction can in any case not be attributed to the slit irregularity, as the signals differ between the two channels.

5.5 From raw data to OPF parameters

As indicated above, there is quite some structure in the row direction of the raw derived parameters. However, since the origin is currently not understood, we have not taken this fine structure into the OPF, even when the structures are reproducible. The structures may originate from other imperfections in the OPF parameters. In that case, it is not wise to correct for it here. Low order polynomials were fitted in the row direction. These polynomials were expanded to provide unbinned parameters, i.e. parameters for each unbinned row. The main reason for this is to facilitate incorporation in the OPF and GDPS.

5.6 Correction in practice

At this stage we have a 5x577 matrix that contains the correction parameters for the inhomogeneous slit illumination. In previous versions of the GDPS, the wavelength assignment was done as follows:

1. Read from the OPF: `<Spectral Calibration Coefficients>` ($c_{OPF,n}$) as well as those that determine the temperature dependence: `<Spectral Calibration Coefficients D>` ($d_{OPF,n}$) and `<Spectral Calibration Coefficients E>` ($e_{OPF,n}$).
2. Rebin these by the applicable binning factor.
3. Calculate the temperature dependence: $c_n(j) = c_{tmp,n}(j) + d_{tmp,n}(j) \cdot \Delta T + e_{tmp,n}(j) \cdot \Delta T^2$

First the relative change in the small pixel radiance must be calculated (Q),

$$Q(j) = 2\frac{SMP(j, Last) - SMP(j, First)}{SMP(j, Last) + SMP(j, First)}$$

This can only be done in case the number of small pixel column radiances per integration period (NSMP) is at least 2.

Then, in the same way as the temperature dependence parameters $d_{OPF,n}$ *and* $e_{OPF,n}$ update c_n the slit inhomogeneity correction parameters are rebinned

$$B_n(j)_{k,m} = \frac{\sum b\_OPF_n(jj)_{k,m}}{f_{binning}(j)}$$

and used to update c_n.

$$c_n^{NEW}(j)_{k,m} = c_n(j)_{k,m} + B_n(j)_{k,m} \cdot Q(j)_k$$

So, in short:

1. Check the number of small pixel column radiances per integration period (NSMP). If less than 2, then raise a flag and make no correction. Exit.
2. Calculate the relative change in the small pixel column radiance: Q.
3. Rebin the OPF parameters needed for the correction: *b_OPF*.
4. Update the wavelength polynomial parameters c_n

6 Results

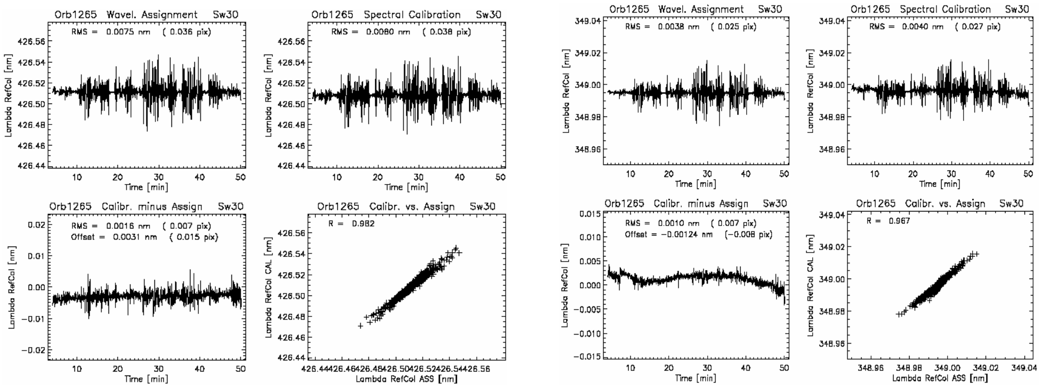
As a test of the algorithm the following sequence was tested. Take the wavelength assignment of the radiance spectra and compare it with the result of the wavelength calibration (from the L1B CAL file). This was done for a number of different orbits, in standard processing mode. This implies that only the central row can be checked, since the wavelength calibration in standard processing is only done for the central row of the radiance spectra. In addition, the wavelength calibration was also performed for all rows in the spectrum and compared with the assignment in the radiance product. These comparisons are made for all sub-channels: UV-1, UV-2 and VIS.
The plots always consist of 4 panels. Top left panel shows the result of the GDPS wavelength assignment. Top right shows the result of the GDPS wavelength calibration algorithm. Bottom right shows the difference between those two and the bottom right plots the result of the calibration versus that of the wavelength assignment. This is mainly to show the correlation.

Note that the wavelength calibration itself is not flawless. But this is the only 'truth' we can compare the assignment to. If the wavelength calibration itself is not more accurate than 0.01 pixel, the assignment, which is based on the result of the wavelength calibration, is not likely to be more accurate. In any case, it cannot be checked. This is not in line with what was set out to be done. The whole idea of replacing the wavelength calibration by a wavelength assignment was based on the assumption that the main parameter driving the accuracy of the wavelength scale was the temperature of the optical bench. And since the temperature was expected to vary smoothly over an orbit – as it does – it was expected that using a temperature corrected assignment would yield more accurate results than individual wavelength calibration results. But this is not the case. So, in view of the large variations in wavelength scale between two subsequent measurements, it seems that the accuracy of the assignment cannot be better than that of an individual wavelength calibration result.

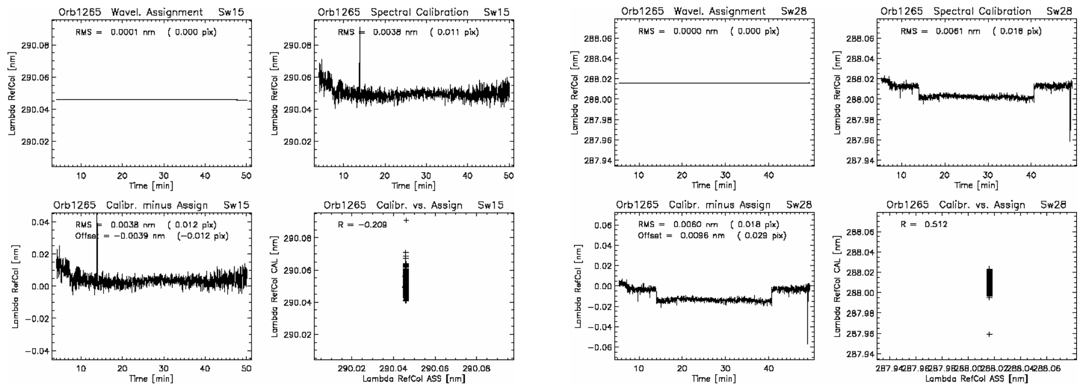
6.1 Swath angle dependence

The next few pages illustrate how well the algorithm works for different swath angles. As an illustration, results for both the central row as well as for more extreme rows are given. For 3 of the 4 panels, the RMS of the signal is given, both in nanometres and in pixels. The bottom left panel in all cases indicates how well the wavelength assignment algorithm works. Basically, there are two parameters that give a quick indication of the quality: RMS and offset. The residual RMS indicates how well the slit correction algorithm works, and the offset shows the magnitude of the error in the first step of the wavelength assignment, before the slit correction. At the end of the subsection, an overview of the main quality parameters for all swath angles are given. Note that there is no slit inhomogeneity correction for the wavelength assignment for the UV-1 channel. The two main reasons for this are that there are no small-pixel column in the UV-1 channel and that the effect of inhomogeneous slit illumination is expected to be much smaller than for UV2 and VIS. From the figures below, it can be seen that this is indeed the case.
Also note that the performance of the correction gets worse at larger swath angles. However, the effect itself is smaller, as can be seen in the figure below, so that the result is relatively independent of row number. Yet another interesting feature is that for row 28 in the UV-1 channel a jump in the wavelength calibration occurs. A physical reason why this should happen is unlikely. It is probably an error in the wavelength calibration algorithm.

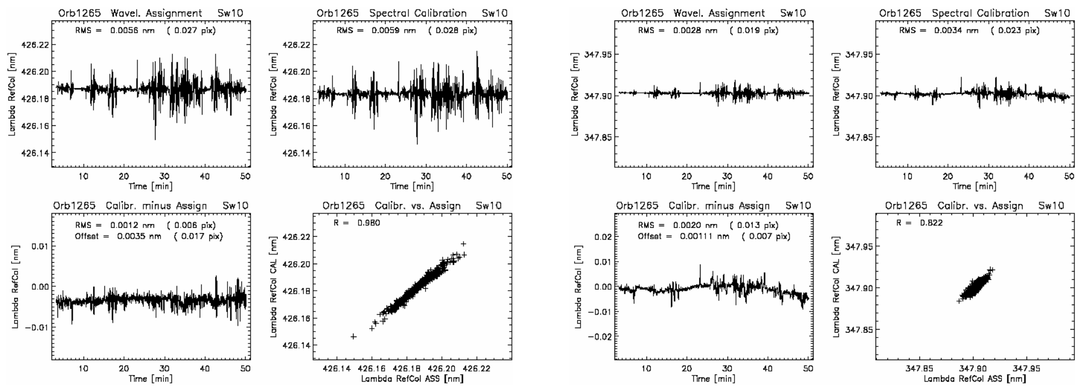
When looking at the figures below we can say that the overall performance of the wavelength calibration appears to be in good shape after version 7 of the OPF, and in particular that the slit inhomogeneity correction algorithm work well.



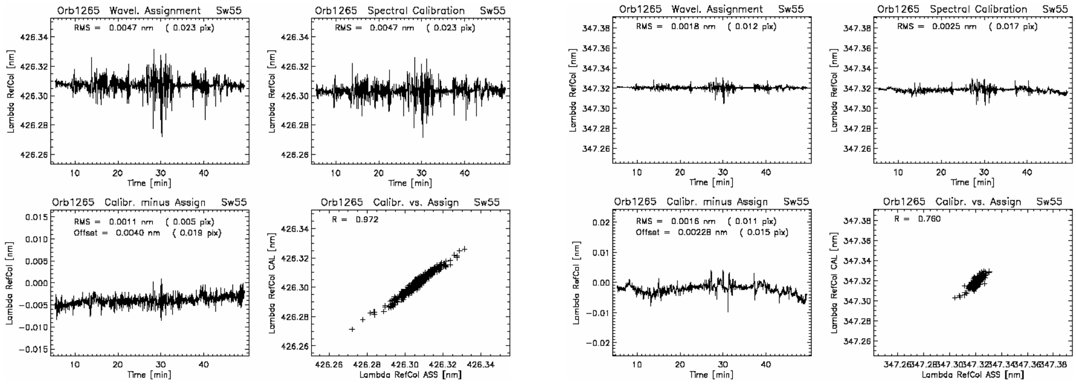
UV2 and VIS Channel, orbit 1265, central row



UV-1 Channel, orbit 1265, central row and binned row 28.



UV-2 and VIS channel, orbit 1265, row 10



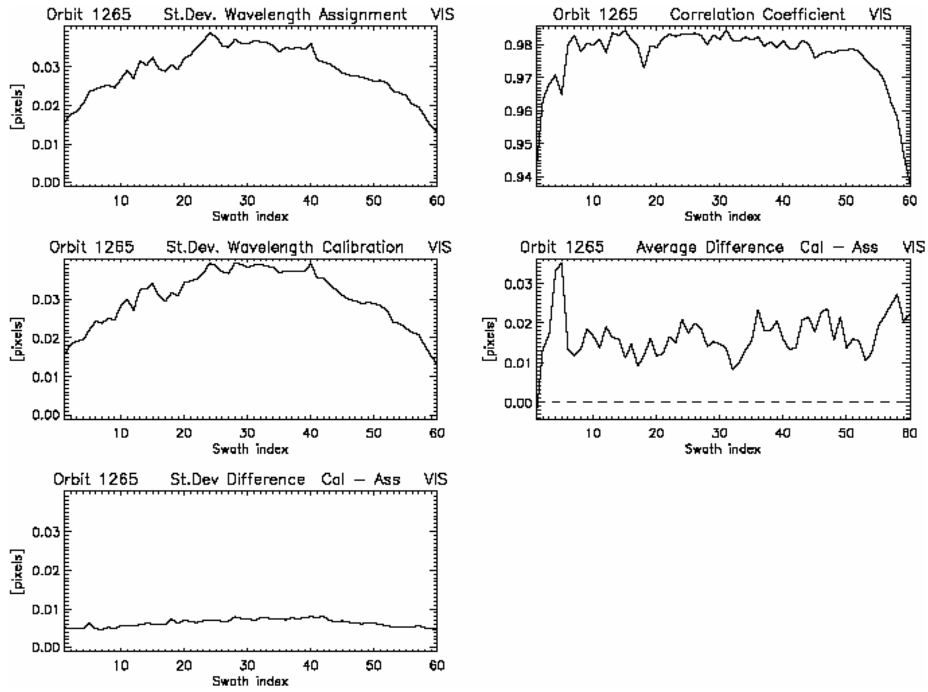
UV-2 and VIS channel, orbit 1265, row 55

6.2 Summary of results for swath dependency.

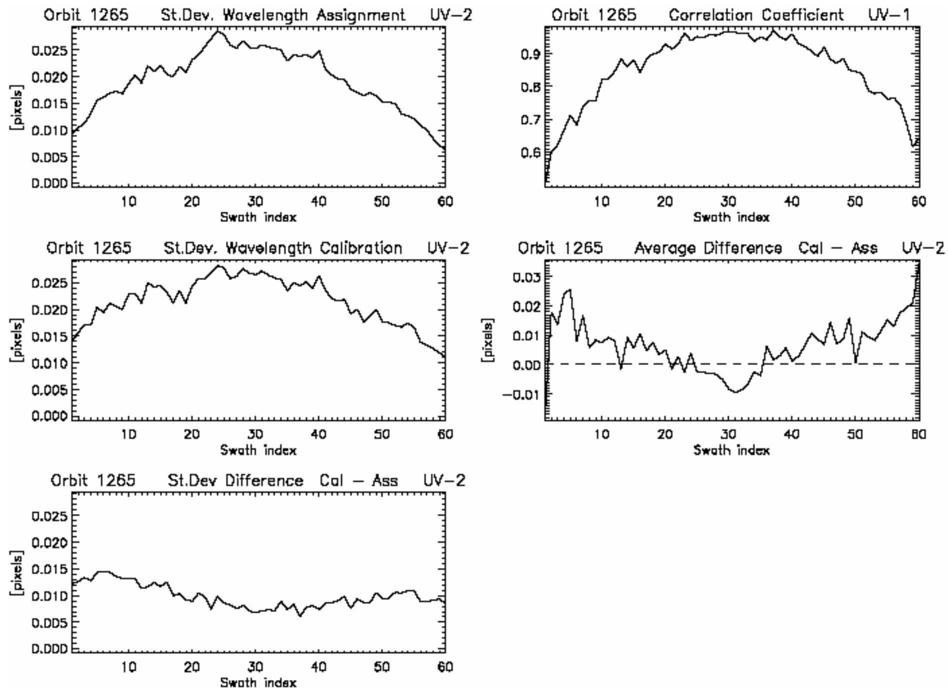
The images below give an impression on how well the algorithm works as a function of swath angle. The left three panels indicate the level of change over an orbit for 3 different observables: Standard deviation of

- Wavelength Assignment
- Wavelength Calibration
- Difference between the two

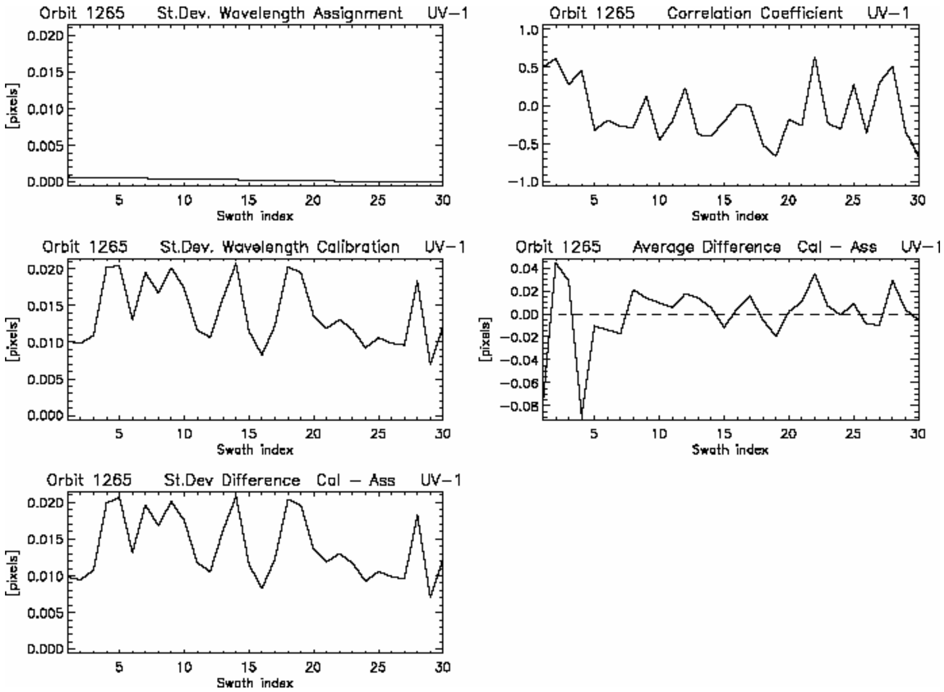
The top two should contain largely the same signal, and for UV-2 and VIS this is indeed the case. For UV-1 the standard deviation in the wavelength assignment signal is virtually zero, because no correction for slit inhomogeneity is made. The bottom of the left panels shows the standard deviation of the difference of the first two signals. This should be less than 0.01 pixel for UV-2 and VIS and less than 0.02 pixels for UV-1. This is almost the case, which shows that the requirement on the knowledge of the wavelength scale can be reached. The right two panels provide different diagnostics. The top right panel shows how the correlation coefficient between wavelength calibration and wavelength assignment changes as a function of row number. The lower panel gives the average difference between the two signals. If the steps preceding this correction step are correct, the average difference should be zero. For the VIS channel there is a clear offset, for the UV channel this offset is smaller. This will be addressed in a future version of the OPF.



VIS channel, overall performance, orbit 1265. The standard deviation has been reduced to less than 0.01 pixel. However, the average difference is still a bit too large.



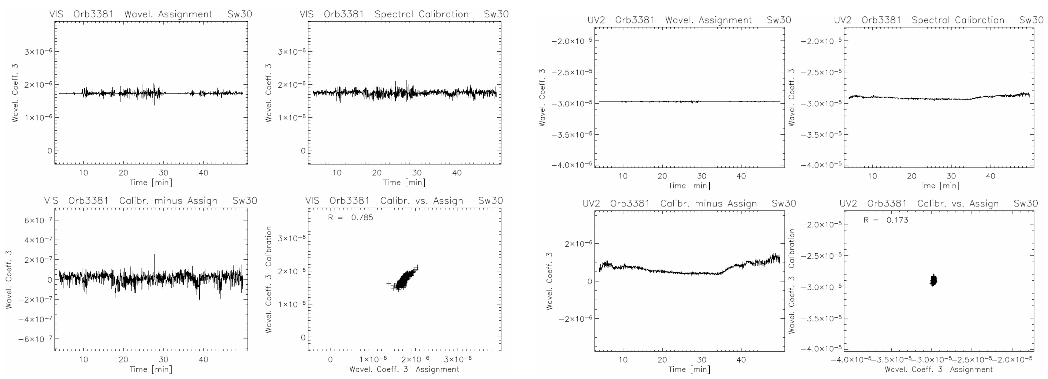
UV 2 channel, overall performance, orbit 1265. The standard deviation has been reduced to approximately 0.01 pixel. The average difference is also very close to 0.01 pixel.



UV1 channel, overall performance, orbit 1265. No reduction in the standard deviation but it is less than 0.02 pixel. Also, the average difference is very close to zero in most cases.

6.3 Wavelength Coefficients of higher order

So far, we have looked at the first polynomial wavelength coefficient. That is, at the wavelength of the reference column of the sub-channel. In order to see to what extent the higher order coefficients are also influenced by the inhomogeneous slit illumination, similar four-panel plots as above are shown below, but in this case for the 2nd order term (i.e. the third coefficient). First, we see that on an absolute scale the match between calibration and assignment is excellent. This means that the first step in the wavelength assignment (before slit inhomogeneity correction) works well. We also see that in the VIS channel, some of the structure seen in the spectral calibration is matched by the assignment. The correlation between the two signals is still almost 80 percent. In the UV-2 channel the correlation is close to zero. However, hardly any rapid variations along the orbit are seen in the spectral calibration result. Therefore, this is the expected result.



Higher order wavelength coefficients in the UV-2 and VIS channels

6.4 Stability in time

In the previous paragraph the swath angle dependence of the quality of the wavelength assignment was shown. In this section the behaviour in time is investigated. When comparing the central row for different orbits we see a very high degree of similarity in the quality of the residues. A marked difference can be seen for the UV-1, where orbits 3238 and 3239 crossed the SAA. This is clearly reflected in the RMS difference. No clear effect of the SAA is seen in the UV-2 or VIS channels. It still has to be studied what causes the erratic behaviour in the UV-1 channel when flying over the SAA. It could be due to a real shift, or, more likely, as no such shifts are found in the other two channels, it is due to a problem with the wavelength calibration algorithm. In that case, the assignment gives better results than the wavelength calibration and there is no cause for concern. However, if the wavelength shifts are real, the assignment in that case is not better than 0.04 pixel RMS, which is a factor of 2 above the required number.
For most orbits, the RMS difference is less than 0.02 and 0.01 pixel for UV1 and for UV2/VIS, respectively. The average difference between calibration and assignment is exactly 0 for the UV-2 channel, but for the UV-1 and VIS channels systematic differences between the two remain. This means that the data field `<Spectral Calibration Coefficients>` in the OPF needs to be adjusted. However, systematic differences between the early orbits and the more recent ones exist. This may indicate an unknown time dependence of the wavelength scale. More work is required to examine this effect, but if it is the case then it may be necessary to update the data field `<Spectral Calibration Coefficients>` for the OPF.

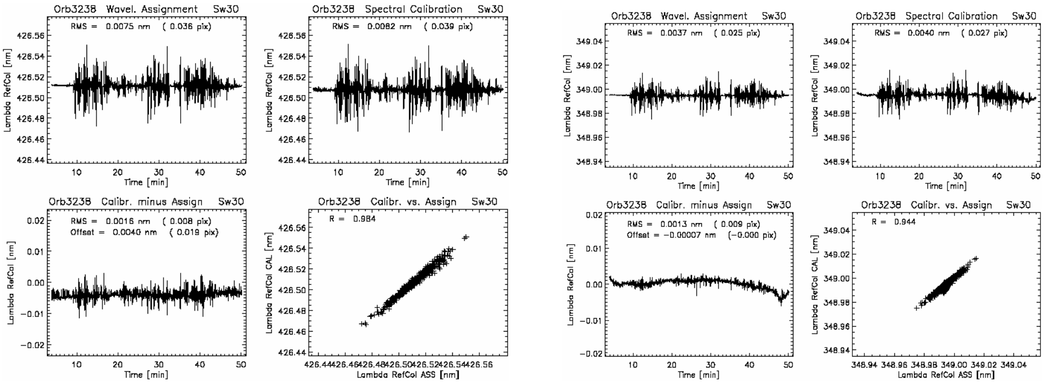
RMS of Calibration minus Assignment in pixels, central row

Orbit	UV-1	UV-2	VIS
842	0.010	0.006	0.008
843	0.010	0.007	0.008
1265	0.012	0.007	0.007
3100	0.015	0.006	0.008
3238	0.030	0.009	0.008
3239	0.040	0.009	0.008
3245	0.018	0.005	0.008
3381	0.017	0.009	0.008

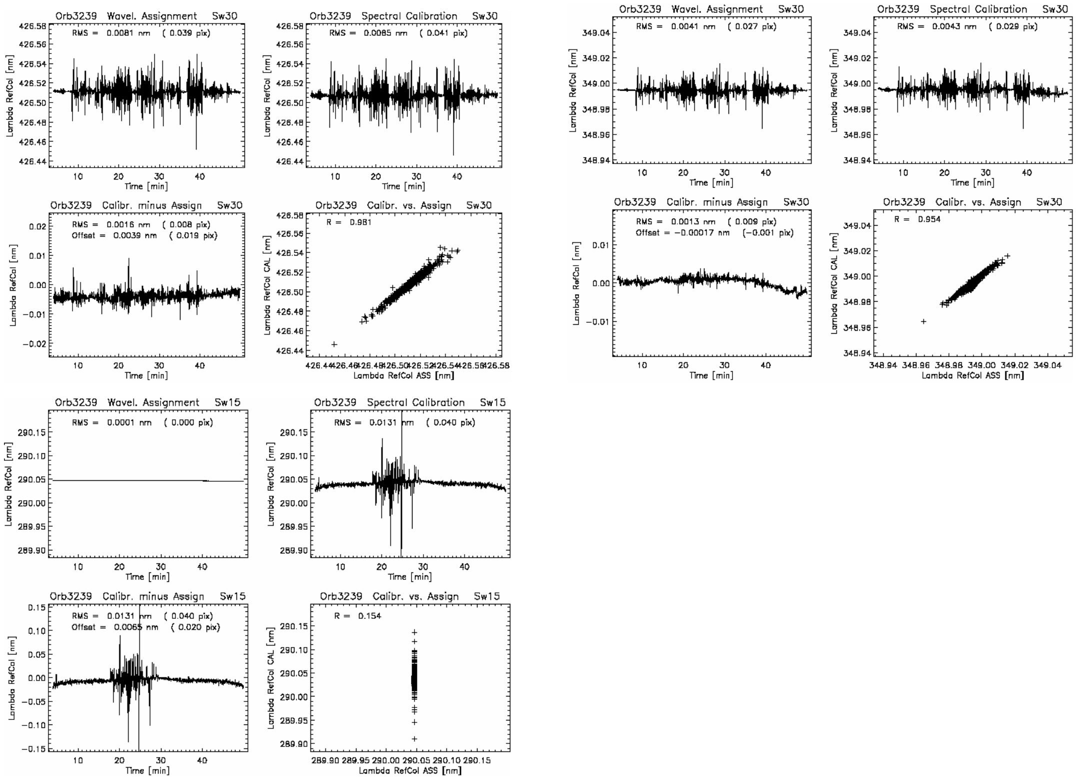
AVERAGE OFFSET (Calibration minus Assignment) in pixels, central row

Orbit	UV-1	UV-2	VIS
842	-0.006	-0.005	+0.015
843	-0.006	-0.005	+0.016
1265	-0.012	-0.008	+0.015
3100	+0.017	-0.004	+0.018
3238	+0.021	-0.000	+0.019
3239	+0.020	-0.001	+0.019
3245	+0.026	-0.003	+0.019
3381	+0.026	-0.000	+0.019

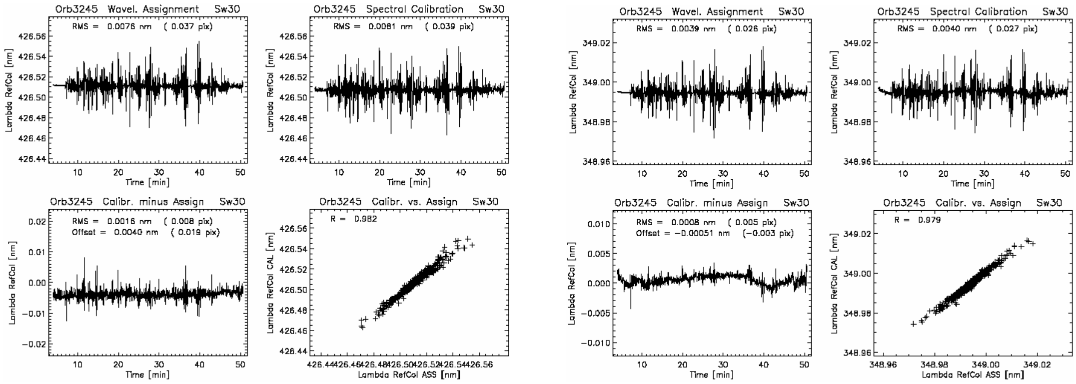
The images below show the familiar 4 panels, for the central row of a number of different orbits. The similarity between the four orbits is especially striking for the UV-2 channel. In the lower left of the 4 panels it can be seen that, apart from the noisy residuals, the difference between the wavelength assignment and the wavelength calibration shows very similar behaviour across the orbit for all four orbits. This behaviour can also be observed in the VIS channel, although in this channel the residual noise (when measured in nm, rather than in pixels) which is slightly larger, somewhat blurs the picture. It was checked whether this could be due to imperfect correction for the temperature dependence of the wavelength calibration. This seems very unlikely. Temperature differences within a single orbit during the Earth measurements are on the order of 0.1 K. As shown in TN-613 (the document that describes the temperature dependence of the wavelength calibration) typical shifts in UV-2 and VIS are less than 0.01 pixel per K. Thus, the wavelength shifts due to temperature changes within the orbit are on the order of 0.001 pixel. This is an order of magnitude smaller than the differences observed here. So, even if no temperature correction were made, this could not explain the observed behaviour.



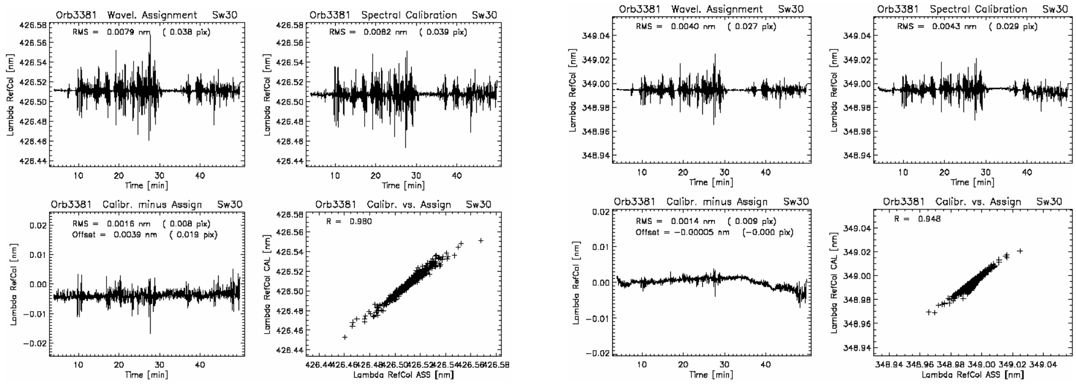
UV-2 and VIS channel, orbit 3238, central row



UV-1, UV-2 and VIS channel, orbit 3239, central row



UV-2 and VIS channel, orbit 3245, central row



UV-2 and VIS channel, orbit 3245, central row

7 Conclusions

From the above results, we can draw the following conclusions.

1. A correction algorithm was implemented in the GDPS (v 0.9.9) and OPF (v 7) to account for the inhomogeneous slit illumination impact on the wavelength assignment. This algorithm improves the wavelength assignments considerably.
2. The correction algorithm as currently implemented in the GDPS (v 0.9.9) and OPF (v 7) for the inhomogeneous slit illumination impact on the wavelength assignment has been tested and has been observed to perform well. After correction, the remaining RMS difference between calibration and assignment is sufficiently low for most cases that the accuracy of 0.01 pixel can be obtained.
3. In the step in the wavelength assignment preceding the inhomogeneity correction, the differences are often still slightly larger than 0.01 pixel.
4. For the UV1 channel no correction is made, and it is seen that the RMS residue is on the order of the 0.02 pixel accuracy required.
5. The parameters used in the OPF for the wavelength assignment slit inhomogeneity correction are smooth functions of row number.

8 Outlook

Even though the present document shows that the implementation of the correction algorithm in the GDPS works well, further refined improvements may still be possible. Especially in the UV-2 channel, the correlation between the measured variations and the applied correction can possibly be improved. However, in order to do this, a more rigorous study of a number of parameters that influence this needs to be performed. First, the wavelength calibration algorithm needs to be further validated. Second, the quality of the wavelength calibration is limited and this in turn limits the accuracy with which the observed variations can be explained, since some of the signal that one tries to correct, is in fact noise. A third thing to consider is possible non-linear contributions to the effect. In first order, the larger the inhomogeneity is, the larger the shift, but some non-linear effect may be present. Another issue to look into in the future is the high frequency variation in the swath direction. The origin of this effect is currently unknown and for this reason it is at this stage ‘smoothed out’.